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Geodynamic settings for Paleoproterozoic gold mineralization in the Svecofennian domain: A tectonic model for the Fäboliden orogenic gold deposit, northern Sweden

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ABSTRACT

Northern Sweden is currently experiencing active exploration within a new gold ore province, the so called Gold Line, situated southwest of the well-known Skellefte VMS District. The largest known deposit in the Gold Line is the hypozonal Fäboliden orogenic gold deposit. Mineralization at Fäboliden is hosted by arsenopyrite-rich quartz veins, in a reverse, mainly dip-slip, high-angle shear zone, in amphibolite facies supracrustal host rocks. The timing of mineralization is estimated, from field relationships, at ca. 1.8 Ga.

The gold mineralization is hosted by two sets of mineralized quartz veins, one steep fault–fill vein set and one relatively flat-lying extensional vein set. Ore shoots occur at the intersections between the two vein sets, and both sets could have been generated from the same stress field, during the late stages of the Svecofennian orogen.

The tectonic evolution during the 1.9–1.8 Ga Svecofennian orogen is complex, as features typical of both internal and external orogens are indicated. The similarity in geodynamic setting between the contemporary Svecofennian and Trans-Hudson orogens indicates a potential for world-class orogenic gold provinces also in the Svecofennian domain.

The Swedish deposits discussed in this paper are all structurally associated with roughly N–S striking shear zones that were active at around 1.8 Ga, when gold-bearing fluids infiltrated structures related to conditions of E–W shortening.

1. Introduction

In recent years, a number of promising gold prospects have been discovered in the Lycksele–Storuman area, commonly referred to as the Gold Line, in northern Sweden (Fig. 1). Many of these prospects are hosted by quartz-vein systems typical of orogenic gold deposits. Such orogenic gold–quartz vein systems typically occupy steeply dipping shear zones that developed syn- to late tectonically within horizontal convergent or transpressional regimes (Goldfarb et al., 2001, 2005; Groves et al., 1998; Kerrich et al., 2000; Sibson et al., 1988). Even though the orogenic gold deposit-type represents an important gold resource on many continents, few research papers have been published on the mineralizations in the Gold Line (e.g. Bark and Weihed, 2007; Bark et al., 2007; Hart et al., 1999). The most studied deposit, the Fäboliden orogenic gold deposit, is also the largest deposit (ca. 58 Mt at 1.05 g/t Au, Lappland Goldminers, 2010). Due to a lack of good exposures and a total absence of oriented drill core it was not previously possible to perform a detailed structural study of the Fäboliden deposit. However, following test mining of the deposit in 2005, better exposures became available, enabling mapping of outcrops within the actual mineralization. These exposures were mapped in detail (scale 1:100) during 2006. In this paper we present the results of this mapping and propose a more detailed tectonic model for the Fäboliden orogenic gold deposit. We also discuss the findings at Fäboliden in relation to Paleoproterozoic gold mineralization in the Svecofennian and Trans-Hudson orogens, with respect to the geodynamic framework (internal/external types of orogens) in both of these orogens.

2. Regional geological setting and metamorphism

The previously considered tectonically semi-continuous 1.9–1.8 Ga Svecofennian orogen (or Svecokarelian orogen; Wahlgren et al., 1996) has been subdivided by Lahtinen et al. (2003, 2004, 2005) into a microcontinent accretion stage, followed by large-scale extension, continent–continent collision, and an orogenic collapse and stabilization of Fennoscandia.

Rifting of the Archean craton of the Fennoscandian Shield commenced around 2.45 Ga, with the final break-up of the craton occurring at about 2.06 Ga, associated with the formation of a large oceanic basin in the south, the Bothnian Basin (Lahtinen et al., 2004, 2005). This basin, which is filled mainly with thick metamorphosed greywacke sequences and subordinate metavolcanic rocks, is interpreted as a fore-arc environment (Weihed et al., 1992). The estimated thickness of the metagreywacke sequence is about 10 km (Lundqvist, 1987), which suggests a deposition along a continental margin (Gaál and Gorbatschev,

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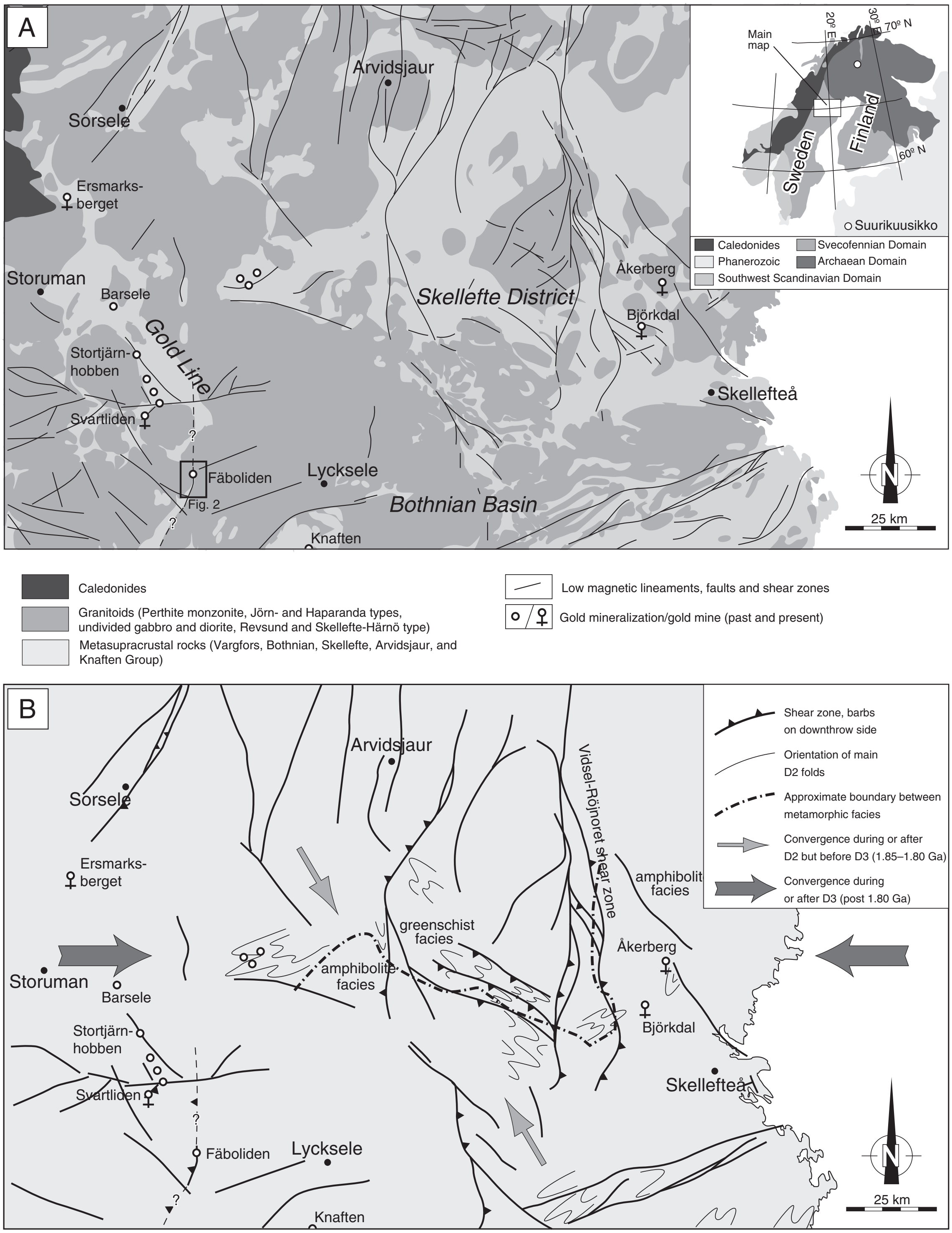

Fig. 1. Simplified geological maps, modified after Bergman Weihed (2001), of the Gold Line and Skellefte District, northern Sweden. A) Bedrock map showing the main rheological relationships, at ca. 1.8 Ga, between granitoids and supracrustal rocks. The area depicted in Figure 2 is indicated. The Gold Line is manifested by the sublinear array of gold mineralizations in the lower left part of the map. B) Tectonic map, with the main shear zones and lineaments featured. (Map coordinates, upper left corner: N7300000/E1550000; lower right corner: N7150000/E1800000, Swedish grid RT90).

1987). The supracrustal rocks of the Lycksele–Storuman area (Fig. 1A), which form part of this metagreywacke sequence, were intruded by ca. 1.90–1.86 Ga calc-alkaline granitoids (Kathol and Weihed, 2005). During the so called Nordic orogeny (1.82–1.79 Ga, Lahtinen et al., 2003, 2005) the supracrustal rocks were successively intruded by ca. 1.82–1.80 Ga S-type granites of the Skellefte–Härnö suite and by ca. 1.81–1.77 Ga alkali-calcic granites of the Revsund suite (Billström and Weihed, 1996; Claesson and Lundqvist, 1995).

P–T analyses suggest that northern Sweden is a low to intermediate pressure metamorphic province, with peak metamorphic pressures of 2 to 4 kbar (Bergman et al., 2001). Earlier studies of the metamorphic conditions in the northern part of the Bothnian Basin indicate that the metasedimentary rocks have been metamorphosed in amphibolite facies (Allen et al., 1996), and locally even in granulite facies (Lundström, 1998).

Regional metamorphism in northern to south-central Sweden peaked intermittently between 1.87 and 1.80 Ga, as is indirectly indicated from field relationships and age determinations of intrusive rocks (Andersson et al., 2006; Billström and Weihed, 1996; Rutland et al., 2001; Weihed et al., 1992, 2002b).

2.1. Structural evolution

No detailed regional structural study has been undertaken in the Lycksele–Storuman area (Fig. 1B, SW corner). However, in the neighboring Skellefte VMS District (Fig. 1A), which has been investigated in greater detail, the supracrustal rocks have been subjected to two major deformation events, denoted D_2 and D_3 (Bergman Weihed, 2001). A similar deformation history has been documented for the supracrustal rocks of the northern part of the Bothnian Basin (Bark, 2005). The D_2 event in the Skellefte District is characterized by tight to isoclinal folds with NE-striking, upright, axial surfaces in the eastern and western parts of the Skellefte District, and by NW-striking axial surfaces in the central parts of the district, as indicated by D_2 trend lines in Fig. 1B. The latest major deformation event, D_3, is characterized by open folds that have axial surfaces striking NNE (Bergman Weihed, 2001).

Titanite that formed or recrystallized within the Vidsel–Röjnoret shear zone (Fig. 1B), in the eastern part of the Skellefte District, indicates two distinct ductile deformation events, at ca. 1.85–1.84 Ga and at ca. 1.80 Ga (Weihed et al., 2002a). The latter of these events, correlating with D_3, is attributed to regional lower-amphibolite facies shearing, contemporaneous with the emplacement of the 1.81–1.77 Ga Revsund granitic suite (Bergman Weihed, 2001; Weihed et al., 2002a, 2003).

2.2. Gold mineralization

During the past twenty to thirty years, hundreds of gold prospects have been discovered in the Finnish and Swedish parts of the Fennoscandian Shield. It is beyond the scope of this paper to discuss all styles of gold mineralization in the Fennoscandian Shield, the focus being instead on orogenic gold deposits, as defined by Groves et al. (1998), in the Skellefte District and the Gold Line, in northern Sweden (Table 1). For recent overviews of gold mineralization in the Fennoscandian Shield, the reader is referred to Eilu et al. (2003) and Sundblad (2003).

In the Skellefte District, the Björkdal and Åkerberg lode gold deposits (Fig. 1) have been mined, while in the Gold Line, the Svartliden deposit is presently being mined. The Fäboliden gold deposit has recently been granted mining permits. All four of these deposits show characteristics typical of orogenic gold deposits, such as structural control, low sulfide- and base metal content, quartz vein systems, and gold as the only economic commodity.

However, the origin of the Björkdal deposit is still debated. Weihed et al. (2003) favors the more classic orogenic gold type of deposit, whereas Broman et al. (1994) and Billström et al. (2009) state, from geochronological, fluid inclusion and stable isotope studies, that the origin and composition of the mineralizing fluids suggest a genetic relationship with the ore-hosting quartz monzodiorite intrusion. However, Broman et al. (1994) also suggest that the Björkdal deposit shows several distinctive similarities with mesothermal gold deposits. Roberts et al. (2006) also emphasize an intrusion-related origin for the gold mineralization at Björkdal, based mainly on Sm–Nd dating of scheelite, and REE characteristics, from the mineralized quartz veins.

In the case of the Björkdal deposit there are two different interpretations regarding the timing of the mineralizing event. Weihed et al. (2003) advocate, based on structural relationships, that the mineralizing event occurred at ca. 1.80 Ga. The evidence for this is the crosscutting relationship between the gold-bearing quartz veins and the S_2 fabric dated at other locations in the Skellefte District at ca. 1.80 Ga. Roberts et al. (2006) and Billström et al. (2009), on the other hand, suggest that the mineralization is older, at ca. 1.90–1.88 Ga, based on radiogenic and stable isotope studies combined with fluid inclusion data. In our view the latter model fails to explain the fact that gold-bearing quartz veins clearly crosscut a tectonic fabric (S_2), which is dated, admittedly with a low degree of precision, at about 1.80 Ga (see Weihed et al., 2003 for a discussion). We therefore retain the model of a late mineralizing event at Björkdal.

At Åkerberg, crosscutting field relationships set the minimum age of mineralization at ca. 1.8 Ga (Sundblad, 2003). At Fäboliden, provisional field evidence also supports a timing for the late stages of gold mineralization at ca. 1.8 Ga (Bark and Weihed, 2003). The timing of mineralization at Svartliden is poorly known.

In addition to the deposits mentioned above, a number of promising gold prospects, for instance the Stortjärnhobben, Knaften, and Barsele occurrences, are presently being explored in the Gold Line (Fig. 1).

3. Fäboliden geological setting and metamorphism

The Fäboliden mineralization (Fig. 2) is hosted by a narrow belt of strongly foliated metagreywackes with intercalated metavolcanic rocks, intruded by late- to post-orogenic, 1.81–1.77 Ga, Revsund granitoids (Billström and Weihed, 1996; Claesson and Lundqvist, 1995). The gold mineralization is dominantly hosted by the metagreywackes, but in the central and southern parts of the deposit mineralization also occurs in the metavolcanic rocks.

For a more thorough description of the Fäboliden rock types see Bark (2005, 2008) and Bark and Weihed (2007).

Fluid inclusion analysis of mineralized quartz veins at Fäboliden indicate pressure conditions during the formation of auriferous quartz veins of 4 ± 0.5 kbar (Bark, 2005; Bark et al., 2007). Regional metamorphic temperatures, deduced from garnet–biotite geothermometry, for the Fäboliden area suggest amphibolite facies conditions at 570–640 °C (Bark and Weihed, 2007). [Note: Bark and Weihed (2007) used microprobe data from garnet and biotite to estimate the metamorphic temperature range (510–640 °C) of the host rocks at Fäboliden. When further scrutinizing that data set, it is evident that the lower end of the temperature range was calculated using an analysis from an anomalously Fe-rich part of one of the garnets. Since it is the exchange of Fe–Mg that is crucial

Table 1
Mined orogenic gold deposits in the Gold Line and Skellefte District, and some prospects presently under evaluation. The large Finnish Suurikuusikko orogenic gold deposit is included for comparison with the younger Swedish deposits.

Deposit	Status	Tonnage	Grade	Timing	Structure	Reference
Unit		(Mt)	(g/t Au)	(Ga)		
Suurikuusikko	m	16	5.1	1.89–1.85	N–NNE shear	Ojala et al. 2007
Åkerberg[a]	c	>1	3	Pre-1.80	E–W shear	Sundblad, 2003
Björkdal	m	>20	2.5	ca. 1.80	NNE shear	Weihed et al., 2003
Svartliden[b]	m	2.8	4.5	?	ENE shear	Dragon Mining, 2005
Fäboliden	p	58	1.1	ca. 1.80	N–S shear	Lappland Goldminers, 2010
Stortjärnhobben	p	nd	nd	?	NNW shear	Bark et al., 2005
Barsele	p	13	1.9	?	?	Northland Resources Inc, 2006

m — mine, c — closed mine, p — prospect, nd — no data.
[a] At Åkerberg, regional scale N–S striking tectonic zones are spatially close.
[b] At Svartliden, NNW striking regional scale tectonic zones are spatially close, but not detected in the mine.

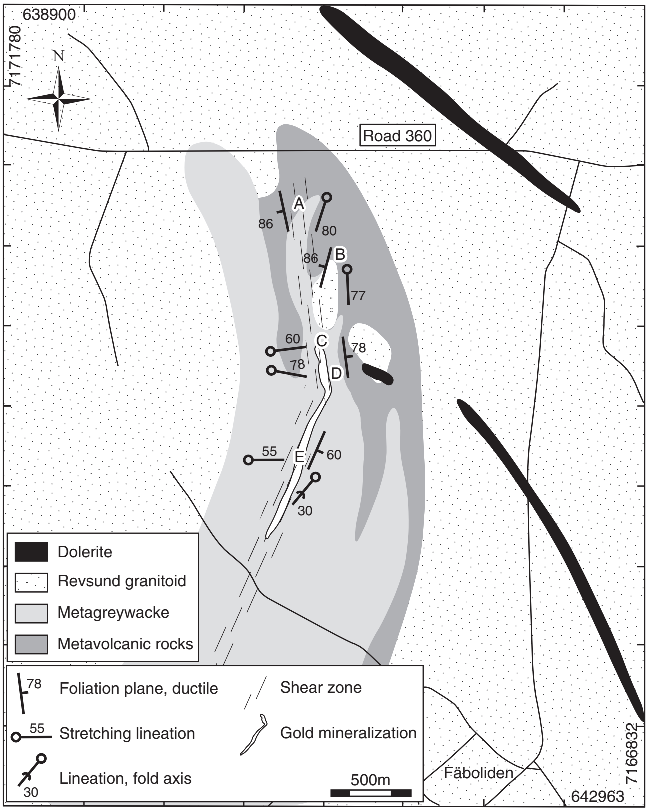

Fig. 2. Bedrock map of the Fäboliden area, with essential structural features indicated. Mapped key areas are indicated with letters A to E. Area E corresponds to the test mine site. Modified after (Björk and Kero, 2002). Coordinates in the Swedish grid RT90.

to the garnet–biotite geothermometer, the anomalous analysis was later excluded from the data set. Hence, we consider that ca. 570 °C is the lower end of the regional metamorphic temperature range in the Fäboliden area.]

3.1. Gold mineralization

The mineralization at Fäboliden is mainly hosted by variably boudinaged graphite-bearing quartz- and sulfide veins confined within a roughly N–S striking shear zone. The width of the proximal part of the mineralized zone is estimated at 30–50 m, on the basis of drill core assays. The sulfides associated with gold (mainly arsenopyrite) are situated in semi-ductile structures as thin veins, and in the necks of the boudinaged quartz veins, parallel to the regional foliation (Fig. 3), indicating a syn- to late-deformation emplacement of the sulfides at Fäboliden (Bark, 2005; Bark and Weihed, 2007).

Gold at Fäboliden is very fine-grained (commonly $<10\ \mu m$) and closely associated with arsenopyrite–löllingite, and stibnite, in the quartz veins (Fig. 4). Gold is also seen as free grains in the wall rock immediately adjacent to the gold-bearing quartz veins.

Proximal to the gold mineralization arsenopyrite is the more common sulfide, but distally pyrrhotite dominates. The total sulfur content in the mineralized zone is 2–3 wt.%, but distal to the mineralization the sulfur content averages about 0.7 wt.%.

The proximal hydrothermal alteration assemblage in the metagreywackes at Fäboliden comprises diopside, calcic amphibole, biotite, with accessory andalusite and tourmaline, and there is a positive spatial correlation between diopside–amphibole–biotite alteration, quartz veining, and gold mineralization (Bark, 2005; Bark and Weihed, 2007). This type of hydrothermal mineral assemblage is common in hypozonal orogenic gold deposits worldwide (Eilu et al., 1999; Hagemann and Cassidy, 2000; Ridley et al., 2000).

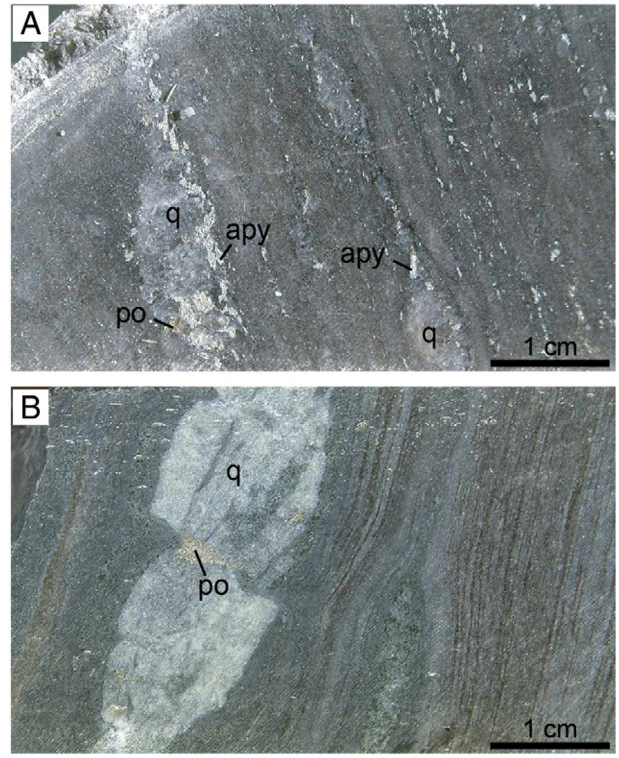

Fig. 3. Drill core sections showing sulfides situated in low-strain positions around metagreywacke-hosted quartz veins at Fäboliden. A) Arsenopyrite-rich quartz vein. B) Pyrrhotite in the neck of a boudinaged quartz vein. apy-arsenopyrite, po-pyrrhotite, q-quartz.

3.2. Timing of mineralization

The roughly N–S striking mineralized shear zone at Fäboliden (Fig. 2) affects the margins of the surrounding, otherwise isotropic, Revsund granite, in a ductile manner. This ductile gold-mineralized fabric, attributed to regional D_3 deformation, is discernible for several meters across the granite contact and then gradually disappears, suggesting that at least the final stages of mineralization syn- to postdate the emplacement of the ca. 1.81–1.77 Ga Revsund granite (Bark, 2005; Bark and Weihed, 2003, 2007). The final stages of gold mineralization could thus be younger than 1.77 Ga. However, the mineralization is hosted by ductile–brittle structures in amphibolite facies and the last known ductile event in this region occurred at ca. 1.8 Ga (Weihed et al., 2002a), which suggests that the timing of mineralization at Fäboliden is around 1.8 Ga. For a more in-depth discussion on the timing of mineralization see Bark and Weihed (2007) and Bark et al. (2007).

4. The Fäboliden quartz vein system

At Fäboliden all supracrustal rocks are moderately to intensely foliated (Bark, 2005). The strike of the regional foliation changes from NNW in the north to NNE in the south (Fig. 2). The dip in the northern part of the mineralization varies from 65°W to 65°E, but is generally subvertical. In the central and southern parts of the deposit, the dip is slightly less steep, averaging 60°E. Primary structures, such as bedding planes (S_0), are rare in the metasupracrustal rocks. However, in a few outcrops, inferred primary bedding planes, parallel to the foliation, can be seen. The regional foliation is interpreted as S_1 since it is axial-planar to minor isoclinal folds that fold these inferred primary bedding planes (S_0). These upright folds (with subhorizontal fold axes) are interpreted as F_1-folds.

A schematic model based on a compressional stress regime during vein formation and late folding of the vein system is shown in Fig. 5 (modified after Robert and Poulsen, 2001). Structural features at Fäboliden are described and interpreted according to this model below.

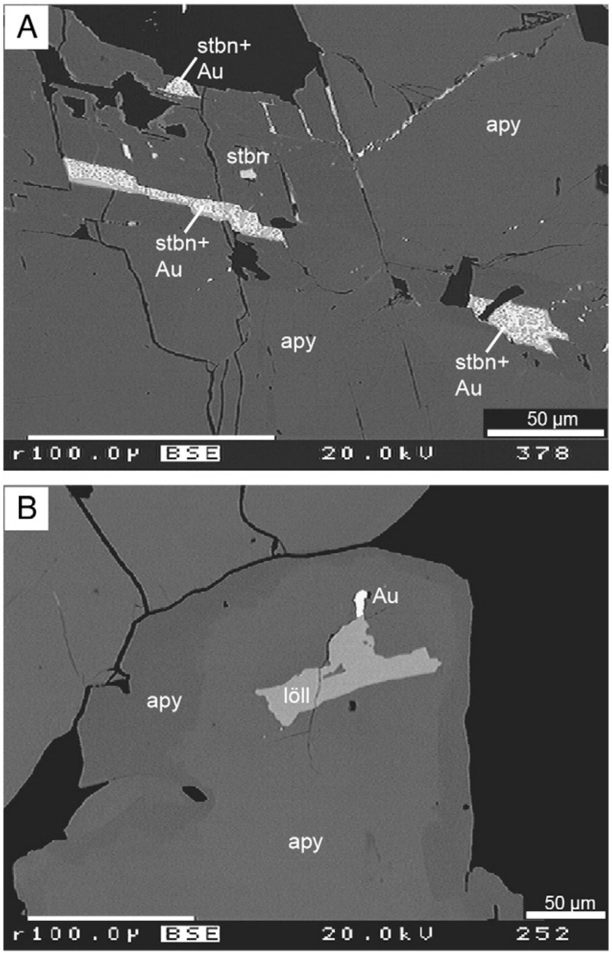

Fig. 4. Backscatter images showing the textural relationship between gold and sulfides. A) Gold, together with probable stibnite, hosted by minute fractures and as inclusions in arsenopyrite. B) Arsenopyrite with löllingite inner core. Au-gold, stbn-stibnite, apy-arsenopyrite, löll-löllingite.

4.1. Ductile shear zones

In fine-grained deformed rocks, a common problem is to find strain markers, i.e. to establish a correct sense of shear. At Fäboliden, kinematic indicators, such as rotated probable phenocrysts (Fig. 6), suggest a dominantly reverse sense of shearing.

In area E, in the south-central part of the mineralization (Fig. 2), discrete shear zones parallel the anastomosing regional foliation. Shearing is heterogeneous and more intense in 10–50 cm wide zones between larger lithons of less deformed metavolcanic rocks. The strike of the shear zones varies from NW to NE, with a dip of ca. 60°E to subvertical (Fig. 7A). In most places the shear zones strike towards NNE in area E, with a few zones striking NW (Fig. 7A). It is unclear if these two systems represent a conjugate set of shear zones or if they are the result of two separate shearing events. The orientation of the majority of shear zones is similar to that of the regional grain shape fabric in area E, indicating that shearing has taken place dominantly along the foliation planes within this shear zone system or that the grain shape fabric is a shear foliation.

In a few places along the shear zone, a vague lineation interpreted as a stretching lineation is seen on the foliation planes in the shear zones (similar to the lineation schematically illustrated in Fig. 5). The lineation is manifested by stretched aggregates of probable diopside and amphibole in the foliation planes. The lineation in the southern and central parts of the shear zone (areas C and E, Fig. 2) trends towards 061–110°, with a plunge of 53–78°, whereas in the northern part (areas A and B, Fig. 2) the orientation of the lineation is 179–202°, with a plunge between 77 and 80° (Fig. 7B). The lineation in the southern and central parts indicates a dominant dip-slip movement in the shear zone, provided that the lineation is a stretching lineation related to shearing. The lineations plunging more steeply towards the south are possibly caused by the rotation of lithons within the shear zone during progressive deformation. This steep south-plunging lineation indicates a small horizontal component to the sense of shear at Fäboliden. A sinistral component, assuming a reverse sense of shear to the shear zone, would result in a lineation orientation like those seen in the northern part of the Fäboliden shear zone.

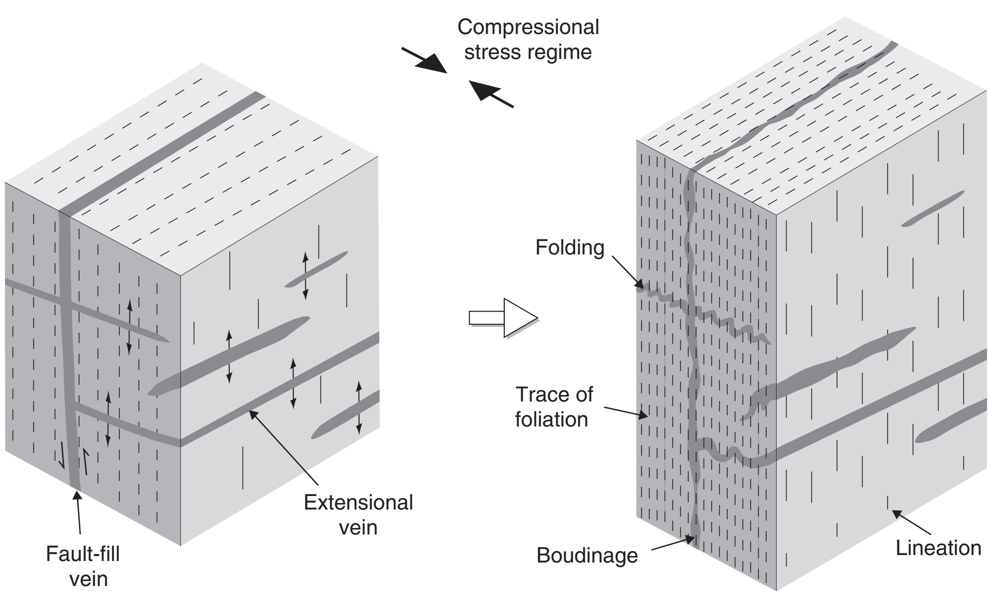

Fig. 5. Structural model, modified after Robert and Poulsen (2001), illustrating the proposed relationship between the ductile shear zone, the fault-fill vein set, and the extensional vein set at Fäboliden.

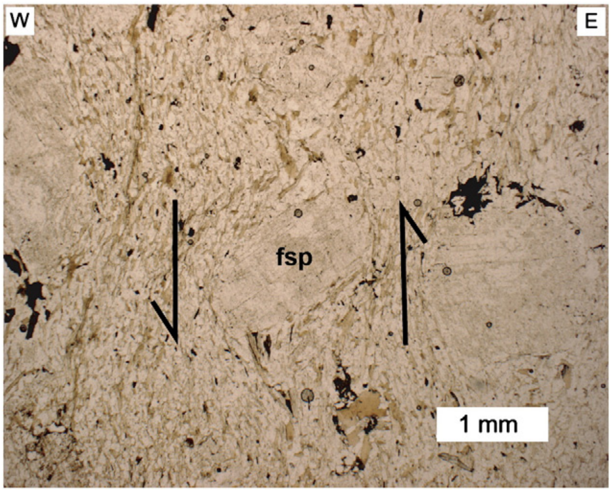

Fig. 6. Photomicrograph (plane-polarized light) showing rotated feldspar porphyroclasts, indicating a reverse sense of shear, with the eastern side up, for the Fäboliden shear zone. The thin section shows a vertical section, perpendicular to the foliation. fsp-feldspar.

4.2. Fault–fill veins

The term fault–fill vein is here used for quartz veins that indicate opening vectors sub-parallel to the vein (after Robert and Poulsen, 2001). The fault–fill vein system at Fäboliden is controlled by and aligned with the discrete shear zones discussed above (Fig. 7A and C). In area E, the mean orientation of the fault–fill vein set is according to the right-hand rule 025/60 (Fig. 7D), whereas the dip of the vein set is steeper in the northern part of the mineralization. The veins are commonly more or less boudinaged, and the thickness of individual veins is 1–5 cm, with some veins up to 20–30 cm in width. The veins commonly contain slivers of foliated wall rock.

4.3. Extensional veins

The term extensional vein is here used for quartz veins that indicate opening vectors perpendicular to the vein and σ_1 of the tentative stress field in the area (i.e. Robert and Brown, 1986), at ca. 1.8 Ga, and which can be formed simultaneously as the fault–fill veins through the process of fault-valve behavior (i.e. Cox et al., 1991, 1995; Sibson et al., 1988). In area E, at Fäboliden, a few relatively flat-lying folded quartz veins have been identified. It is only at this site (area E, Fig. 2) that it is possible to get good three-dimensional exposures within the mineralized zone. The width of the largest extensional quartz vein in area E is 10–20 cm (Fig. 8A). The exact orientation of this extensional vein was not possible to measure, but a subparallel, thinner vein suggests a strike and dip of 012/28 for the flat-lying vein set (Fig. 7D). Also, a handful of cm-thick folded arsenopyrite-rich quartz veins, with a similar orientation as the thicker vein, are seen in this area. The axial planes to these thinner folded veins are subparallel to the regional

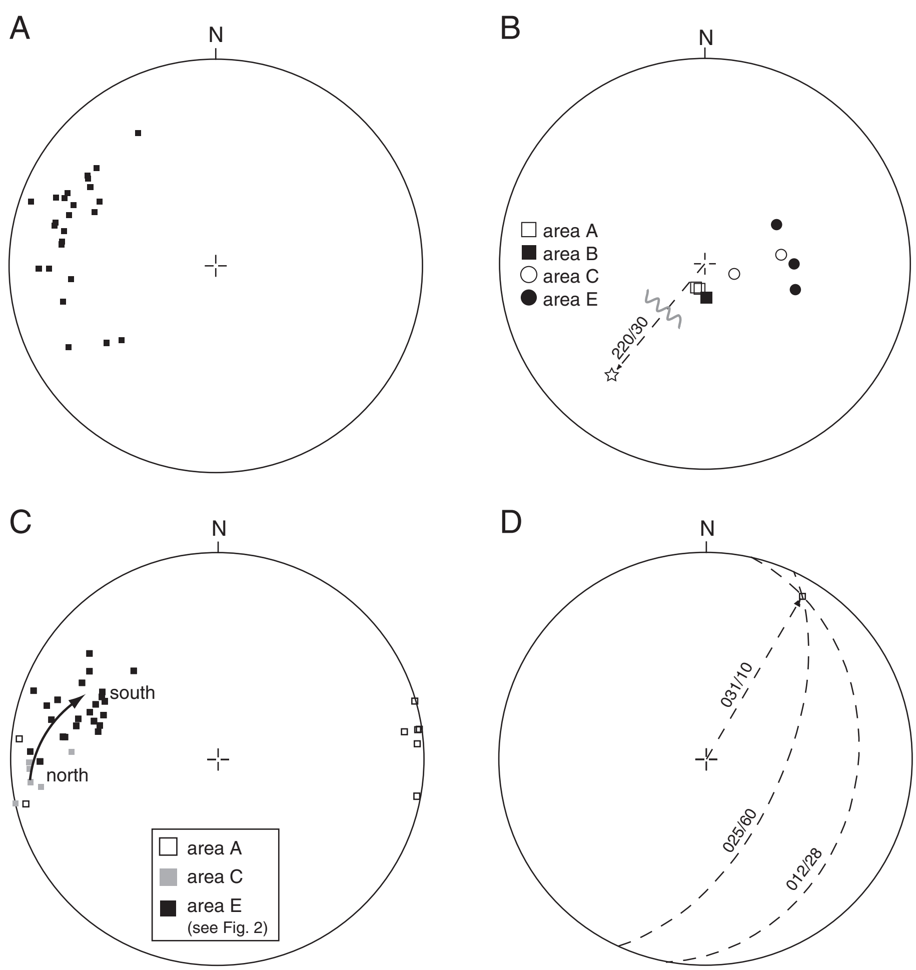

Fig. 7. Stereographic projections of Fäboliden structural data (Schmidt net, lower hemisphere). A) Poles to discrete shear zones (planes) in area E (n=30) B) Stretching lineations, with a fold axis (220/30) at site E indicated by a star. C) Poles to foliation planes, indicating a shift in the strike in the northern part of the mineralization. D) Relationship between the fault-fill vein set (mean of 025/60) and the extensional vein set (012/28) in area E, with an intersection between the two vein systems plunging 10° towards 031°.

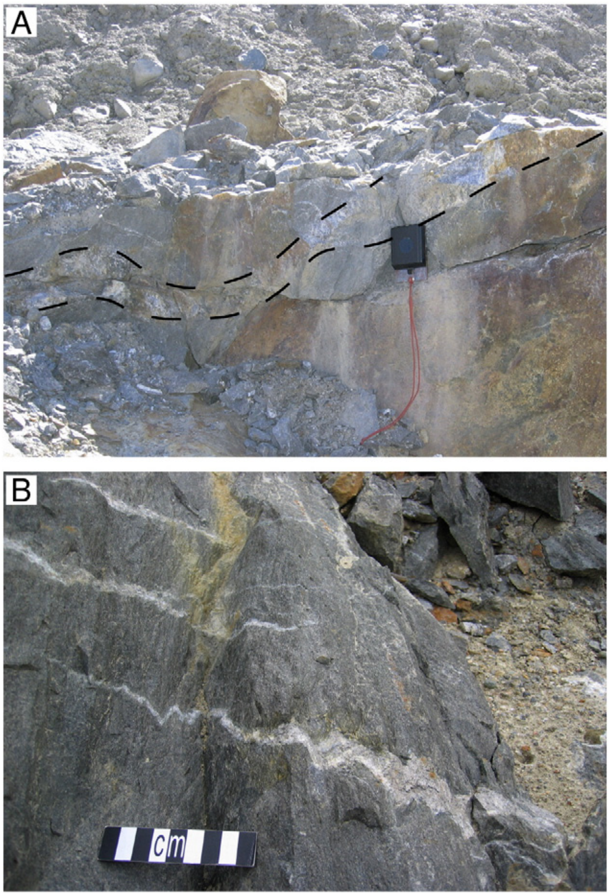

Fig. 8. Extensional veins at Fäboliden. A) Large relatively flat-lying extensional gold-rich vein in area E, indicated by dashed lines. B) Thinner veins of the same orientation. The axial planes to the folds in the arsenopyrite-rich cm-wide veins are roughly subparallel to the regional foliation which in this particular outcrop is about 030/55. Both photographs are taken towards south, and the vertical faces in the outcrops are oriented perpendicular to the strike of the foliation.

foliation (Fig. 8B). A rough estimate of one of the fold axes indicates a trend and plunge of 220/30.

To better characterize the extensional quartz vein system mineralogically, additional work is needed. However, from mapping and whole rock geochemistry it is indicated that the extensional veins are rich in arsenopyrite and that the gold concentration is high.

5. Structural interpretation of the Fäboliden gold–quartz vein system

At Fäboliden, there is a shift in the orientation of the shear zone between the southern and northern parts (Fig. 2). The northern part strikes towards NNW, whereas the southern part strikes towards NNE (Fig. 7C). Where the shear zone is close to the metavolcanic rocks in the northern part of the Fäboliden area it seems to refract from the metavolcanic rocks towards NNW, as indicated by a shift in the strike of the foliation. The northern part is also steeper, commonly subvertical whereas the dip is roughly 60°E in the south. A difference in rheology between the metagreywacke and the metavolcanic rocks during progressive deformation could explain the shift in orientation of the foliation. Also, differences in the geometry of the contact between the supracrustal rocks and the surrounding granite could generate local variations in the stress field, and thereby affect the orientation of the shearing, resulting in different strike orientations between the northern and southern parts of the shear zone system. A good example of this phenomenon is the Granny Smith gold deposit, in the Yilgarn Block of Australia, where gold mineralization is controlled by the shape of the contact between a granodiorite and a sedimentary sequence (Ojala et al., 1993).

The steep (60–90°) fault–fill veins at Fäboliden are believed to have been emplaced during reverse shearing, as suggested by rotation of probable phenocrysts controlled by the foliation (Fig. 6). Fault–fill gold–quartz veins are commonly associated with high-angle reverse structures (Fig. 9) formed during compression (Sibson and Scott, 1998). Under such conditions, subhorizontal extensional veins likely form as hydraulic fractures at mid-crustal levels (Robert and Poulsen, 2001). In a compressional stress field shallow-dipping (ca. 30°) reverse shear zones are expected to form (Hodgson, 1989; Ramsay, 1980), but commonly fault–fill veins are hosted by higher-angle structures. This is possibly due to reactivation of pre-existing high-angle structures and lithological contacts as it is likely that additional stress is channeled through already existing structures, instead of the formation of new low-angle reverse faults (Cox et al., 1995; Sibson et al., 1988).

At the Archean Sigma mine, in the Canadian Abitibi greenstone belt, there is no consistent crosscutting relationship between the subhorizontal extensional veins and the steeper fault–fill veins, thus there is strong argument that both vein sets formed roughly contemporaneously (Sibson et al., 1988). Although the timing relationship between the different vein sets at Fäboliden have not been possible to determine, it is possible that the fault–fill and the extensional vein sets are roughly coeval, like at the Sigma mine.

The regional tectonic evolution of the northern part of the Bothnian Basin is poorly known. However, in the neighboring Skellefte District most north-striking shear zones indicate reverse, eastern block up sense of movement (Bergman Weihed, 2001). This is also seen at Fäboliden where the steep reverse shear zone indicates eastern side up (Bark, 2005; Bark and Weihed, 2007).

The shear zone at Fäboliden locally indicates both a sinistral and a dextral horizontal component. However, based on the proposed stretching lineations, the main movement at Fäboliden appears to be dip-slip (Fig. 7B). For gold–quartz vein deposits this is commonly the case (i.e. the Sigma mine, Val d'Or; Robert and Brown, 1986; Sibson et al., 1988). If the main movement is dip-slip, then small differences in the horizontal movement can result in an alternating horizontal shear component observed along the shear zone system. This appears to be the case at Fäboliden. Also, possible variations in strain intensity and the geometry (dip) of the contacts of the surrounding granite could explain the local differences in the horizontal shear component.

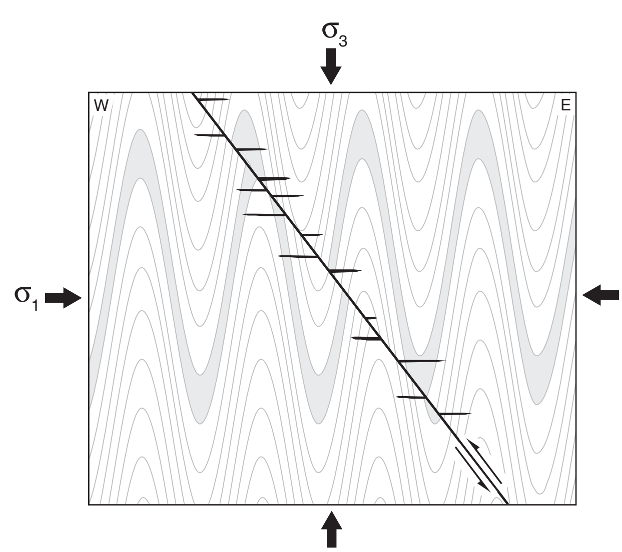

Fig. 9. Schematic model of a high-angle reverse shear zone, with horizontal extensional veins associated with the steep fault-fill vein. No scale. Modified after Sibson and Scott (1998).

5.1. Ore shoots

In area E (Fig. 2), discrete high-strain zones parallel to the shear zone boundaries are separated by lithons that are less deformed. The high-strain zones are characterized by an anastomosing geometry, a feature commonly seen at all scales in shear zones and shear zone systems (Bell, 1985; Hodgson, 1989). These high-strain zones commonly form a three-dimensional network surrounding low-strain blocks in the bedrock. The low-strain lithons, between the shear zones, commonly host extensional veins (Hodgson, 1989; Robert and Brown, 1986). At Fäboliden, relatively flat-lying, 1–20 cm wide extensional veins are seen in low-strain lithons in area E. The two vein sets, the fault–fill veins and the extensional veins, intersect and the calculated intersection lineation between the two vein sets plunges 10° towards 031° (Fig. 7D). Ore shoots are commonly associated with extensional veins, and the intersections between extensional and fault–fill veins are common sites of elevated gold concentrations (Cox et al., 1991; Robert and Poulsen, 2001). The intersection between the extensional and fault–fill veins in area E is unusually gold-rich, with up to 20 g/t Au, compared to the average grade (1.05 g/t Au) of the Fäboliden mineralization, thus emphasizing the importance of these structures for gold concentration.

Bends in shear zones, such as the refraction of a shear zone due to rheological contrast between rock units, are common sites of linear ore shoots (Hodgson, 1989; Robert and Poulsen, 2001). At Fäboliden, drill core assays indicate more gold-rich sections, compared to the average grade, where the shear zone is close to the metavolcanic rocks in the northern part of the mineralization (Fig. 2), coincident with a bend in the shear zone.

In summary, the Fäboliden orogenic gold mineralization is controlled by a roughly N–S striking reverse, mainly dip-slip, high-angle shear zone. The mineralization is dominated by two sets of mineralized quartz veins; one steep fault–fill vein set and one relatively flat-lying extensional vein set. At least two types of ore shoot are present at Fäboliden. At sites where the fault–fill and extensional vein sets crosscut, gold concentrations are elevated. In addition, drill core assays from the northern part of the mineralization indicate elevated gold content where the shear zone bends towards NNW. Both types of ore shoot are common in gold–quartz vein deposits globally.

6. Implications for the global geodynamic framework

Barley and Groves (1992) demonstrated that the temporal distribution of some major types of ore deposits (i.e. porphyry copper, VMS, and orogenic gold) correlate well with the cyclic formation and break-up of supercontinents. In a global perspective, orogenic gold formation correlates well with periods of growth of juvenile continental crust, specifically in subduction–accretion type orogens within the supercontinent cycle (Barley and Groves, 1992; Goldfarb et al., 2001; Kerrich et al., 2005). The two globally more important time periods for orogenic gold formation are 2.8–2.55, and 2.1–1.8 Ga (Barley and Groves, 1992; Goldfarb et al., 2001, 2005; Groves et al., 2005; Kerrich et al., 2000). During the latter of these time periods, the supercontinent Columbia is suggested to have formed through amalgamation of crustal segments along collisional orogens that today are recognized in nearly every major continental block (Rogers and Santosh, 2002; Zhao et al., 2002, 2004).

During supercontinent assembly, two main types of orogeny have been recognized; internal and external orogens (Murphy and Nance, 1992). Internally the supercontinent is formed from continent–continent collision along one major suture, whereas externally continental growth is manifested by Cordilleran-type terrane accretion onto a continental craton. Large-scale metallogenic differences between these two types of orogens are indicated by the existence of giant lode gold provinces in Cordilleran-type accretionary orogens, whereas gold districts in continent–continent collisional orogens (i.e. the 2.0–1.8 Ga Trans-Hudson orogen in North America, and the 1.9–1.8 Ga Svecofennian orogen in northern Europe) tend to be smaller and less gold-rich, even though the deposits display mineralogical, structural, and geochemical features very similar to giant lode gold systems formed in external orogens (Barley and Groves, 1992; Kerrich and Wyman, 1994; Kerrich et al., 2000). A lack of deep-rooted fluid conduits in internal-style orogens may be the reason for the lower gold concentrations, as compared to external accretionary orogens where giant lode gold systems occur (Kerrich and Cassidy, 1994; Kerrich et al., 2005). Furthermore, due to extensive crustal thickening, rapid uplift and erosion following a continent–continent collision the chance of preservation diminishes for ore deposits in this tectonic environment (Barley and Groves, 1992; Kerrich et al., 2005). Hence, internal orogens are commonly considered less prosperous with respect to orogenic gold formation. There is, however, a well-known exception in the structurally controlled giant Homestake lode gold deposit that has since 1876 produced in the excess of 1200 metric tons of gold (Caddey et al., 1991; Morelli et al., 2010). The Homestake deposit is situated in the Trans-Hudson orogen, and this orogen should be considered relatively less mineralized due to its internal-type nature. However, the particular segment that hosts the Homestake deposit has features commonly seen in external orogens (Kerrich et al., 2000), thus indicating a complexity in the Trans-Hudson orogen, making it more prosperous than a strictly considered internal orogen.

The Trans-Hudson orogen extends from the interior of North America, through southern Greenland (Ketilidian orogen), into the contemporary Svecofennian orogen in Fennoscandia (Hoffman, 1990; Kerrich and Cassidy, 1994; Lewry and Collerson, 1990; Zhao et al., 2002, 2004). The complex ca. 1.9–1.8 Ga Svecofennian orogen is subdivided by Lahtinen et al. (2003, 2004, 2005) into 1) 1.92–1.87 Ga, microcontinent accretion, 2) 1.86–1.84 Ga, large-scale extension of the accreted crust, 3) 1.84–1.79 Ga, continent–continent collision.

As a consequence of the complex nature of the Svecofennian orogen Lahtinen et al. (2011) recently suggested that the late stages of the 1.84–1.79 Ga collisional orogen is manifested by either continent–continent collision or by an advancing Cordilleran-type accretionary orogen. During this time period the far-field stress regime, for the western part of the Fennoscandian Shield, rotated from NW–SE to E–W (Weihed et al., 2005), indicating a change and complexity of the geodynamic framework. Thus, the nature of the late-Svecofennian collisional orogen is complex and still debated.

In Fennoscandia, age data on orogenic gold mineralization is scarce (Table 1). However, it is possible to divide most of the deposits into three main periods of orogenic gold formation; 2.72–2.67, 1.90–1.86, and 1.85–1.79 Ga (Weihed et al., 2005). These periods are suggested to reflect times of progressive growth of the Fennoscandian Shield, towards south-west, as is manifested by a zonation in the timing of orogenic gold mineralization, with older deposits (i.e. Suurikuusikko; in Fig. 1) in the north-east and younger deposits (i.e. Björkdal, Åkerberg, and Fäboliden) in the central part of the shield (Bark and Weihed, 2003; Weihed et al., 2005). A lateral zonation, like the one described above, with respect to the timing of orogenic gold mineralization is typical of Cordilleran-type orogens (external), where both the ages of igneous rocks and timing of gold mineralization young towards the ocean, reflecting the episodic growth of continental crust by terrane accretion (Goldfarb et al., 1997; Kerrich et al., 2005). Hence, similar to the Trans-Hudson orogen, also in the Svecofennian orogen there is a complexity, with respect to orogenic type (internal/external), suggesting a potential for more gold-rich orogenic gold discoveries.

During the late stages of the Svecofennian orogen, during the 1.82–1.80 Ga so called Nordic orogeny (Lahtinen et al., 2003, 2004, 2005), orogenic gold formation took place in the Svecofennian domain. In the Skellefte District and the Gold Line, in the Swedish part of the Svecofennian domain, orogenic gold formation occurred at c. 1.8 Ga, during post peak-metamorphic cooling of the crust. In the eastern part of the Skellefte District, at Björkdal, the timing of orogenic gold mineralization is suggested at about 1.8 Ga (Weihed et al., 2003). The same age has also been proposed as a minimum age for mineralization at the Åkerberg lode gold deposit (Sundblad, 2003). In the central-western part of the Gold Line, at Fäboliden, field relationships suggest a timing, for at least the late stages of mineralization, of ca. 1.8 Ga (Bark and Weihed, 2003, 2007). In southern Finland Saalmann et al. (2009) bracketed orogenic gold formation at 1.82–1.79 Ga. Noteworthy here is, besides the contemporary formation of orogenic gold deposits, the alignment of the Gold Line district in northern Sweden and the gold mineralized Häme belt investigated by Saalmann et al. (2009) in southern Finland, showing a north-western trend that parallels the boundary to the Archean craton in the north-east (Fig. 1, inset).

The Swedish orogenic gold deposits discussed above are all hosted by tectonic zones that strike roughly N–S (Table 1). At Åkerberg, the ore-hosting deformation zone strikes roughly E–W. However, there are also both minor N–S striking shear zones within the mineralization and a number of regional scale N–S striking shear zones in the Åkerberg area. The mineralization at Svartliden is hosted by an ENE-trending structure, although here too, large-scale NNW-striking tectonic zones occur in proximity of the deposit. In these two cases it is possible that mineralization is hosted by subsidiary structures to the regional scale N–S striking tectonic zones. Hence, although a direct relationship with mineralization is not manifested everywhere the orientation of the regional scale tectonic zones, at least spatially associated with gold mineralization, strike roughly N–S.

7. Conclusions

The tectonic evolution during the Svecofennian orogen is complex, as indications of both internal (inferred continent–continent collision, and a relatively unmineralized nature) and external (younging of gold deposits towards the ocean) orogens are discussed here. Geodynamic similarities between the contemporary Svecofennian and Trans-Hudson orogens (hosting the giant Homestake lode gold deposit) indicate a potential for world-class orogenic gold deposits also in the Svecofennian domain.

The Swedish part of the Svecofennian domain, notably the Skellefte District and the Gold Line, is still an under-investigated area, with respect to orogenic gold mineralization. The Swedish deposits discussed in this paper are all structurally associated with roughly N–S striking tectonic zones that were active at around 1.8 Ga, when auriferous fluids infiltrated structures related to the conditions of E–W shortening.

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